THE EFFECT OF SURFACE TENSION
ON FLOODING VELOCITIES IN A PACKED COLUMN

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PREFACE: NOMENCLATURE USED

A - Cross-sectional area of column, sq. ft.

F - Fraction of free volume in packed tower, cu.ft./cu.ft. tower volume

g - Acceleration of gravity ft./(sec.)(sec.)

G - Superficial mass velocity of gas (based on empty column), lb./(sec.)(sq.ft. cross sectional area)

h - Packed height of column, ft.

L - Superficial mass velocity of liquid (based on empty column), lb./(sec.)(sq.ft. cross sectional area)

S - Surface area of packing, sq.ft./(cu.ft. of tower volume)

ΔP - Pressure drop across the packed section, inches of water

U_G - Superficial gas velocity based on entire column cross-section ft./sec.

U_L - Superficial liquid velocity based on entire column cross-section ft./sec.

ρ_G - Density of gas, lb./cu.ft.

ρ_L - Density of liquid, lb./cu.ft.

γ_w - Surface tension of water, dynes/cm.

γ_s - Surface tension of sterox solution, dynes/cm.

μ - Liquid viscosity, centipoises

ϕ - Correction factor for gas density, $\left(\frac{\rho_G}{\rho_a}\right)^{\frac{1}{2}}$ where ρ_a is density of air

SUMMARY

Flooding velocities were measured for the countercurrent air-water system in a 4 inch diameter, 4 ft. high laboratory glass column, packed with Berl saddles, and the data correlated by two methods suggested in the literature. The flooding velocities for solutions of various surface tensions, achieved by the addition of a small amount of a detergent to water, were then determined and found to vary greatly from those with water.

Empirical surface tension correction factors were found for each correlation used, which bring the data for water and the various solutions into a single line within reasonable limits.

The flooding velocities of toluene and air were determined and found to be different from water and air, though found not nearly so much so as the solutions with a detergent.

It was found that surface tension has an appreciable effect on flooding velocity, especially when the surface tension is reduced by means of a wetting agent in solution with the liquid. It is recommended that further investigations be made with other packing materials, and other liquids of different surface tensions.

INTRODUCTION

Even though packed columns are a common piece of process equipment, used for distillation, absorption, extraction, etc., all the factors affecting their design have not been completely defined. The capacity of packed columns is limited by their tendency to flood, and in countercurrent gas-liquid operation the flooding velocity is affected by the physical properties of the gas and liquid, as well as the flow rates, and characteristics of the packing.

The need for determining limiting conditions in packed columns for countercurrent contacting operations has long been recognized and a number of investigators have determined pressure drops and flooding velocities for various packing materials. A variety of liquids and gases have been studied for the purpose of correlating liquid and gas density, liquid viscosity, and packing characteristics with liquid and gas flow rates at the flooding point.

The usefulness of these correlations for design purposes is obvious. Whereas an economic balance should determine the best operating condition, a knowledge of flooding points is helpful in determining the maximum flow rates of the two streams and in estimating the optimum rates when there is insufficient data to make a precise economic balance.

After a review of the literature on flooding velocities, it was felt that there was need for more data on the effect of surface tension of the liquid, especially when the surface tension was altered by the addition of a small amount of a surface active agent. The reasons for this conclusion were twofold: first, the surface tension effect could be more directly studied, since a small amount of wetting agent changes neither the density nor viscosity, and second, it was felt that the reduction in surface tension, by means of a wetting agent, would possibly be a measure of the tendency of the liquid to foam or bubble, a phenomenon which has not been heretofore studied as such.

One group of investigators, Sherwood, Shipley, and Holloway[5], studied the effect of surface tension and found that it was not a factor in flooding, but they used methanol, aqueous methanol, and aqueous butyric acid. All of these liquids had densities and viscosities different from water and none of them had active surface characteristics, nor did they give a measure of the tendency of the liquid to form bubbles.

Thus the object of this investigation was to determine the flooding characteristics of one gas and liquid system, then vary the surface tension of the liquid without altering its other physical properties, and to study the effect of this change on the flooding behavior.

REVIEW OF LITERATURE

Sherwood, Shipley and Holloway[5] varied the gas and liquid density and the liquid viscosity and surface tension in a 2 inch diameter packed column, determining flooding velocities by visual observation. They correlated the results by plotting:

$$\frac{U_G^2 S}{g F^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{.2} \qquad vs. \qquad \frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$$

(where U_G is superficial gas velocity, S is surface area of packing, g is acceleration of gravity, F is fraction of void space in packed section, ρ_G and ρ_L are density of gas and liquid respectively, μ is liquid viscosity, L is mass velocity of liquid, and G is mass velocity of gas.) This correlation is dimensionless except for the μ term. Surface tension does not appear in this correlation since Sherwood, et al., found it to have no appreciable effect on the flooding velocity. Their conclusion was based upon measurements using aqueous butyric acid and various methanol solutions.

Elgin and Weiss[6] investigated different packing materials using the air-water system in a 3 inch diameter glass column and found reasonable agreement with the correlation of Sherwood, et al. They also investigated liquid holdup in the column, and found that this was a measure of flooding velocity which gave similar results to the pressure drop vs. gas velocity (at constant liquid rate) curve suggested by White[3] and Mach. This latter method of determining flooding velocity consists of plotting, at constant liquid rate, the pressure drop across the packed bed vs. the gas rate. If pressure drop across the column is plotted along the ordinate and gas rate on the abscissa on log-log graph paper, the resulting curve can be represented very nearly by either 2 or 3 straight line segments. The flooding point is defined as the intersection of the upper two straight lines. Beyond the flood point the slope of the highest line is nearly vertical. Elgin and Weiss also found a linear relation between $\sqrt{U_G}$ and $\sqrt{U_L}$ to exist at the flood point for any given packing and system (U_G is gas velocity, U_L is liquid velocity, based on empty column). This is an empirical relationship, but was found to hold true over the range of their data.

Bertetti[7] developed a semi-theoretical equation for flooding which was not substantiated by later experimental work by Bain and Hougen[9].

Sarchet[8] compared visual and graphical (method of White[3]) flooding velocities with an 8 and 21/32 inch pyrex column using the air-water system. The large column reduced wall effects and Sarchet found that the relative magnitude of visual and graphical flooding velocities depended upon the packing size, among other factors. He investigated three packings and reported that some of the discrepancies in previous work could be attributed to the method for determining the flood point. It appeared that small packings ($\frac{1}{2}$ inch or less) gave graphical flooding points equal to or less than the visual points, while larger packings yield graphical points higher than the visual. Sarchet correlated his results by a plot of $\frac{L\phi}{G}$ vs. $\frac{G}{\phi}$ (G and L are mass velocity of gas and liquid respectively, and ϕ is gas density factor, $\sqrt{\frac{\rho_G}{\rho_a}}$ where ρ_G is gas density and ρ_a is density of air). This correlation corrects for gas density but liquid properties are not included. He also gave empirical equations based on this plot, for water and any gas, with a factor for packing diameter. This, however, is less general than the Sherwood, Shipley and Holloway correlation since a separate plot would be needed for each liquid.

Bain and Hougen[9] conducted tests on three oils and three gases, using five different packings, to provide more data on the effect of viscosity, density, and packing characteristics. They used an 8 21/32 inch glass column, and applied the graphical method of determining flooding velocity. Bain and Hougen found the exponent on the viscosity term in Sherwood, Shipley and Holloway's correlation to .16 instead of .2. They extended the work by plotting the logarithm of the ordinate group vs. the $\frac{1}{4}$ power of abscissa group, which showed the relationship to be linear and gave the following equation for flooding points:

$$\log\left[\frac{U_G^2 S}{g F^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{.16}\right] = b - \left(\frac{L}{G}\right)^{\frac{1}{4}}\left(\frac{\rho_G}{\rho_L}\right)^{\frac{1}{8}}$$

where b is a constant and appears to have one value for all sizes of rings and helices and another for all Berl saddles. The data of Bain and Hougen fall about 10% above the line of Sherwood, Shipley and Holloway at low values of $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$ and 40% below at high values (above .4), crossing at .2. Bain and Hougen could not correlate their results by means of the Bertetti[7] equation.

Schoenborn and Dougherty[10] studied five commercial packings with air as the gas, and three liquids, water and two oils of different viscosities. They used visually determined flood points but found these to vary little from the break in the pressure drop curve, however, they stated that there was no consistency as to whether the visual or graphical point was higher. Schoenborn and Dougherty correlated their results by the method suggested by Colburn and used by Sarchet[8], that of $\frac{L\phi}{G}$ vs. $\frac{G}{\phi}$ at flooding (ϕ being taken as unity, in this case). They multiplied the $\frac{G}{\phi}$ term by kinematic viscosity to an exponential depending upon the packing, varying from .12 to .33. This gave good results for their data and is somewhat simpler than the Sherwood et al., or Bain and Hougen relation.

Lobo, Friend, Hashmall and Zenz[11] undertook to study all published data on flooding velocities to determine whether a more satisfactory method of correlation could be devised, since the published data scattered widely. They found that the major discrepancies in published work were due to the wide range of values reported for S/F^3 (S is surface area of packing and F is free volume of packed section). Accordingly, they recalculated all published data on the basis of measured value of S/F^3, which they found experimentally. The method of packing was found to be most significant, and by recalculating the data available, taking the method of packing into account, Lobo, et al., reduced the average deviation, using Sherwood, Shipley and Holloway's grouping of variables, from 29.8% to 11.5%. This is of importance to design engineers since it reduces the error in calculated tower diameter (if L/G is assumed to be known) from a maximum of 18.5% to a maximum of 6.0%.

After Lobo, et al. had reduced the deviations in published data, the method of Sherwood, Shipley and Holloway, seemed to be adequate for design purposes.

DESCRIPTION OF EQUIPMENT

The column was constructed of a 3 7/8 inch inside diameter glass cylinder, 4 feet high, with a 3 inch gate valve well below the packing support and the air inlet just below the valve. (See figure 1) The packing support, which was wire mesh of a size just smaller than the packing, and glass column rested on a 3 3/4 inch flange and rubber gasket of the same size. Liquid seal on the bottom of the column was assured by a U-tube which the liquid ran out of, the top of which was on a level of 2 inches below the air inlet. The liquid overflowed from the U-tube into a reservoir and was thence recycled to the distributor head, through one of two calibrated rotameters, of the bead guide tube type. The distributor head was a metal cap with 1/16 inch holes drilled in a concentric circular pattern. It was found necessary to use a head with smaller and fewer holes at the very low liquid rates and in all cases the distribution was observed to be regular across the packed bed.

The air was supplied by the laboratory compressor, and was cleaned by passing it through glass wool and any liquid droplets were removed by a cyclone separator before it entered the system. The air rate was measured by one of two standard orifices, constructed according to A. S. M. E. specifications*. There was a 0.5 inch orifice in a 1 inch pipe, and 0.2 inch orifice in a 3/4 inch pipe. The pressure drop across

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*Report, "Fluid Meters" of the A. S. M. E., Special Committee on Fluid Meters, 4th Edition, 1937, American Society of Mechanical Engineers, New York

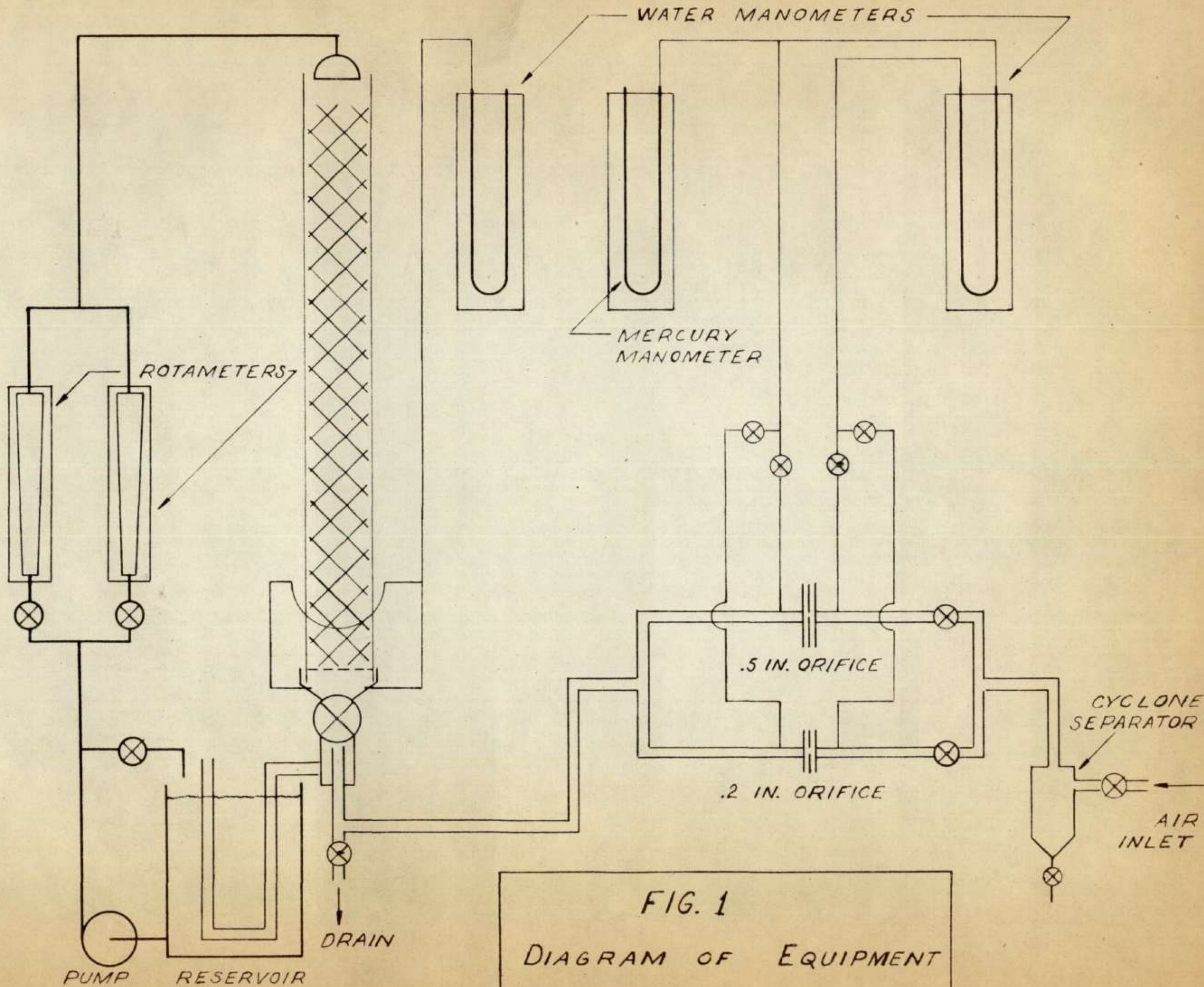

FIG. 1

DIAGRAM OF EQUIPMENT

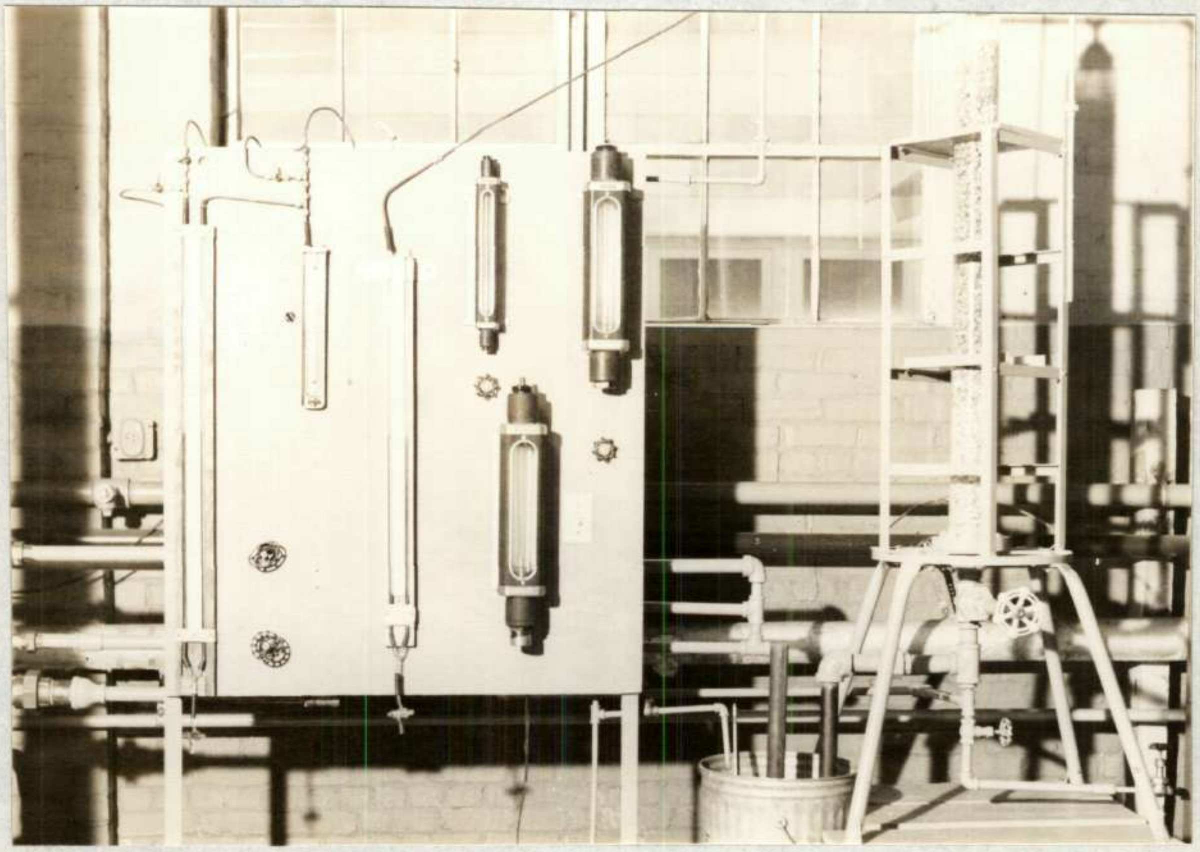

Figure 2. Front View of Apparatus

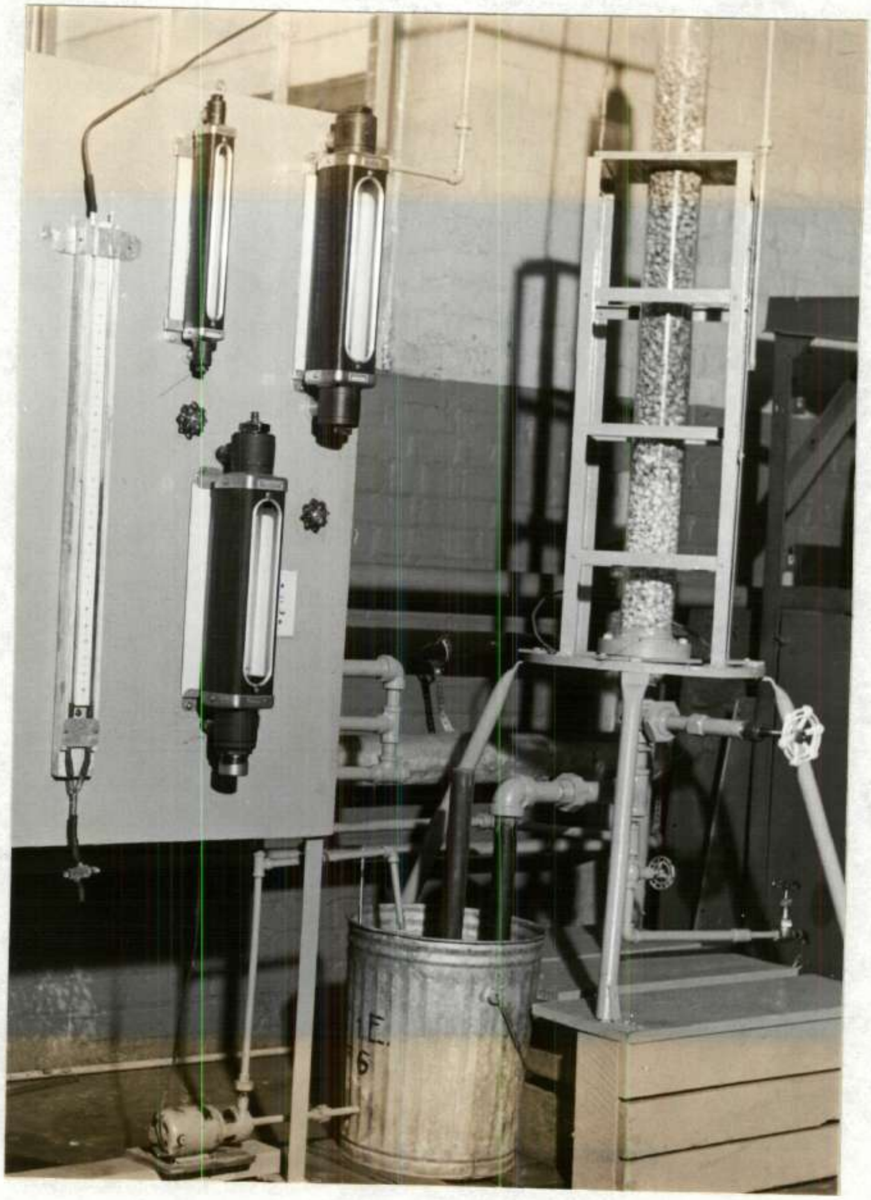

Figure 3. View of Column

the orifice being used was measured by a water manometer, and the downstream pressure by a mercury manometer. Copper tubing was used for orifice-to-manometer connections. The .2 inch orifice was calibrated by means of a gas meter, and the orifice coefficient was found to be within 2% of the predicted value. A valve was provided just below the air inlet on the air line, to drain any liquid which happened to get into the air line. All valves used on the air system were gate valves.

The pressure drop across the packed bed was measured by means of two pressure taps located just below the packing support on opposite sides of the column and connected together then to one leg of a water manometer, the other leg of which was open to the atmosphere. It was found by experiment at maximum gas flow that the pressure just inside the top of the column above the packed bed, was so nearly atmospheric as to be not discernible on a water manometer.

The column was packed to a height of 3.5 feet while filled with liquid, the packing units (.5 inch Berl saddles) being dropped in individually. This was done to duplicate most of the published work on small packed columns. It is interesting to note here that Lobo, et al.[11] found this method (wet packing without shaking the column) to give much lower values of S/F^3 (S is surface area of packing, F is free volume or void space in packing) than dry dumping. However, after the author's column had been in operation for some time, the voids were carefully measured by adding a measured quantity of water to the packing and noting the height to which it filled the column, and S/F^3 calculated and found to be comparable to Lobo's values for dry dumping. This is difficult to explain since the packing had not settled during operation, as the column was carefully observed from time to time for evidences of settling. The measured values were used in the correlations, and the flooding line of Lobo, et al. and Bain and Hougen duplicated closely.

EXPERIMENTAL PROCEDURE

The method of determining flood points was essentially the same as that used by previous investigators. An arbitrary liquid rate having been established, the gas rate was increased in increments, the pressure drop across the packed bed being allowed to come to a constant value at each incremental gas rate. The gas rate was increased until absolute flooding, characterized by violent entrainment and head of 3 or 4 inches of water built up on top of the packing, was reached.

After numerous determinations at various liquid rates with water, during which the column was cleaned out and fresh water put in the reservoir about every two days, a solution of sterox* was put in the system. Having previously determined the approximate number of drops of sterox per liter to give a desired surface tension, it was possible by adjustment and dilution to achieve any desired surface tension, down to the minimum of about 34 dynes/cm. The measurements of surface tension were made with a DuNouy Tensiometer calibrated with distilled water, and with care, results were reproducible within 1.0%. The solution was recycled through the column for an hour, the surface tension of two samples determined, then used in the column in the same manner as tap water had been. After every other run the surface tension was checked to be sure it did not change during the experiment. The sterox solutions were found to be stable as to surface tension, once they had been thoroughly

*Sterox SK (trade name) Monsanto Chemical Co. (Condensation product of ethylene oxide and dodecyl mercaptan) mixed. In measuring the surface tension of solutions, samples were taken of the liquid running out of the column as well as the bulk of the solution in the reservoir, and no solution was used until these gave identical results with the tensiometer.

The procedure was repeated for four different solutions with surface tensions of 67, 60, 48 and 37 dynes/cm. as compared to 72 dynes/cm. for water.

The system was next cleaned and dried and toluene (surface tension 28 dynes/cm. installed. Four determinations were made over the range of liquid rates available and each one checked, after the liquid rotameters had been calibrated for toluene by experiment. The surface tension of the toluene in the system was checked after the runs and found not to have varied.

VISUAL OBSERVATION OF THE COLUMN

The behavior of the column was essentially that described by Elgin and Weiss[6] and Bain and Hougen[9]. At medium and high liquid rates, holdup or a head of foaming liquid was observed in the lower part of the column. This head of agitated liquid was seen to increase and when it reached the top of the packing a head of liquid was built up above the packed bed. This final condition was stable and water continued to flow through the column, however, violent entrainment always accompanied this condition. This was noted as the visual flooding point.

At low liquid rates, the holdup or agitation was seen to occur at several points almost simultaneously rather than moving steadily up the column, but the final flooded condition appeared in exactly the same manner at all liquid rates. This behavior, holdup or agitation starting at the bottom of the column, seems to be peculiar to Berl saddles from the description in the literature, however, the results, when plotted on a pressure drop vs. gas velocity curve, look the same as with other packings and are reproducible.

The behavior with sterox solutions was the same except that the foaming was more pronounced and flooding occurred at a lower gas rate as shown in "Treatment of Data and Results".

As an additional precaution, the packing was removed with the packing support left intact and an effort was made to flood the column with only the packing support in place, as a check on whether the support might cause the initial agitation which eventually built up to flooding. It was impossible to get an appreciable pressure drop across the packing support alone, or to get any water head built up on it except at the maximum water rate used in the investigation, 2.66 lb./(sec.)(sq. ft.), and the gas rate necessary to build up a liquid head in the bottom of the column at this liquid rate was the maximum available with the equipment, .30 lb./(sec.)(sq. ft.). As a comparison, with the packing in place, and the same water rate, the column flooded at a gas rate of .03 lb/(sec.) (sq. ft.).

This would indicate that the effect of any constriction in the bottom of the column or in the packing support was certainly negligible in the operation of the packed column, since the liquid head began to build up at a gas rate of 10 times as much without the packing in place.

TREATMENT OF DATA AND RESULTS

Since the graphical method of determining flooding velocities, suggested by White[3] and Mach, has been found to be more reliable than visual observation by most authors, this method was used. The pressure drop per foot of packed bed is plotted on the ordinate and either U_G or G on the abscissa (ρ_G varies very little so that U_G differs from G by practically a constant value) and the upper break in this curve, above which the curve is nearly vertical, is taken as the flood point.

In general there was no difficulty in locating the flood point on the curves. (Sample curves shown in fig. 4.) The absence of a lower break in the curve defined as the "load point", was noted in some instances, as it has been by other investigators. In a few instances, there was some doubt as to the break being the actual flood point, since the portion beyond the break was appreciably inclined from the vertical. In most of these cases another determination was made, however, at very low liquid rates, the pressure drop at any condition is not as stable as at high liquid rates and the points tend to scatter somewhat, thus the curve is not as well defined. This is probably the reason for the slightly wider scatter of the points at low values of L/G, when the data is plotted on a general correlation.

The flooding point data was plotted on the correlation of Sherwood, Shipley, and Holloway[5] (see fig. 5) and also by the method suggested by Colburn and used by Sarchet[8], and Schoenborn and Dougherty[10] (see fig. 6). The latter method is the less general of the two, but

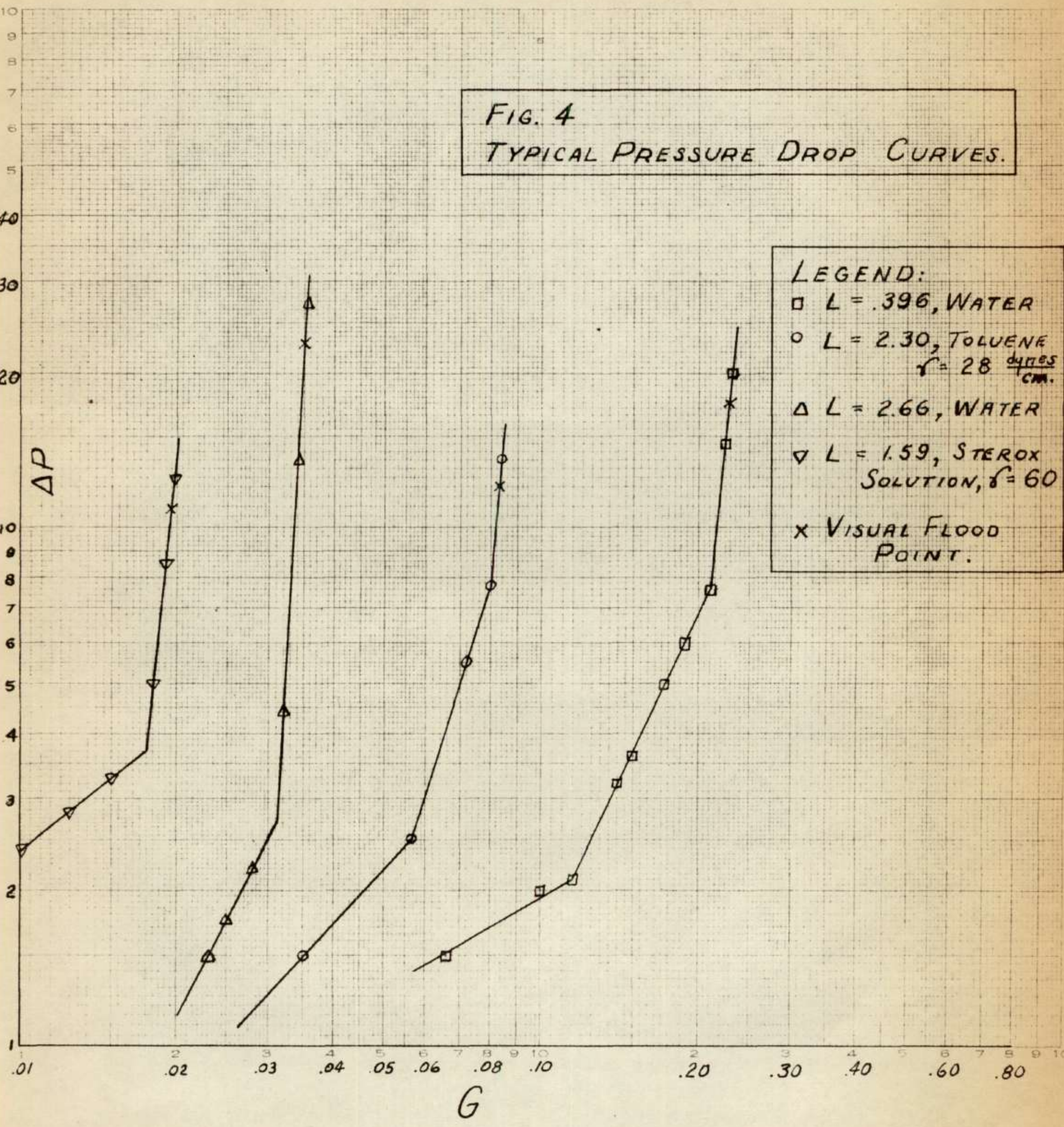
FIG. 4
TYPICAL PRESSURE DROP CURVES.
LEGEND:
□ L = .396, WATER
○ L = 2.30, TOLUENE γ = 28 dynes/cm.
△ L = 2.66, WATER
▽ L = 1.59, STEROX SOLUTION, γ = 60
× VISUAL FLOOD POINT.
ΔP
G
.01
.02
.03
.04
.05
.06
.08
.10
.20
.30
.40
.60
.80
1
2
3
4
5
6
7
8
9
10
20
30
40

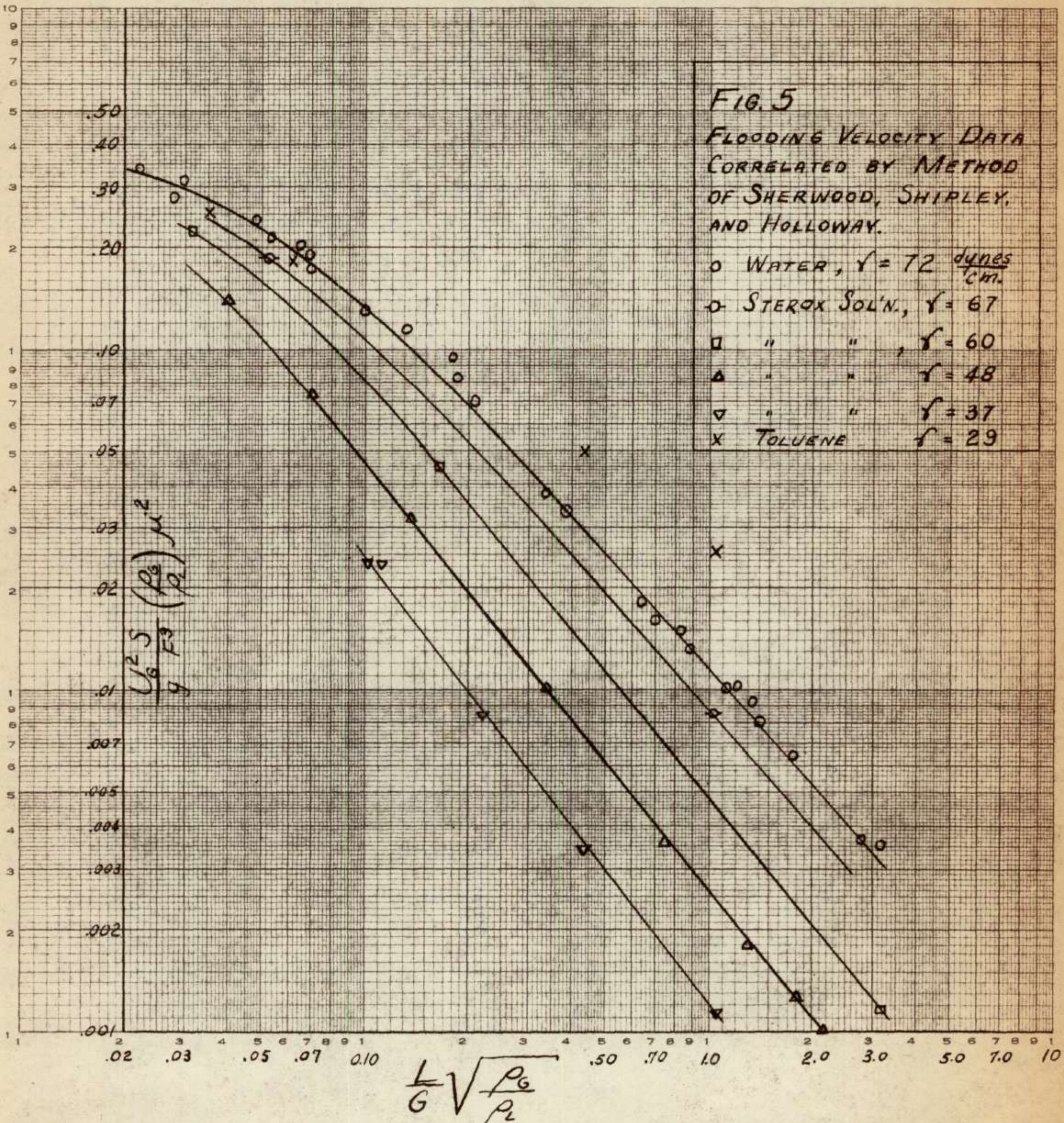
FIG. 5
FLOODING VELOCITY DATA CORRELATED BY METHOD OF SHERWOOD, SHIPLEY, AND HOLLOWAY.
o WATER, γ = 72 dynes/cm.
-o- STEROX SOL'N., γ = 67
□ " " , γ = 60
△ " " γ = 48
▽ " " γ = 37
× TOLUENE γ = 29
$\frac{U_G^2 S}{g F^3} \left(\frac{\rho_G}{\rho_L}\right) \mu^2$
$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$
.001
.002
.003
.004
.005
.007
.01
.02
.03
.05
.07
.10
.20
.30
.40
.50
.02
.03
.05
.07
0.10
.50
.70
1.0
2.0
3.0
5.0
7.0
10

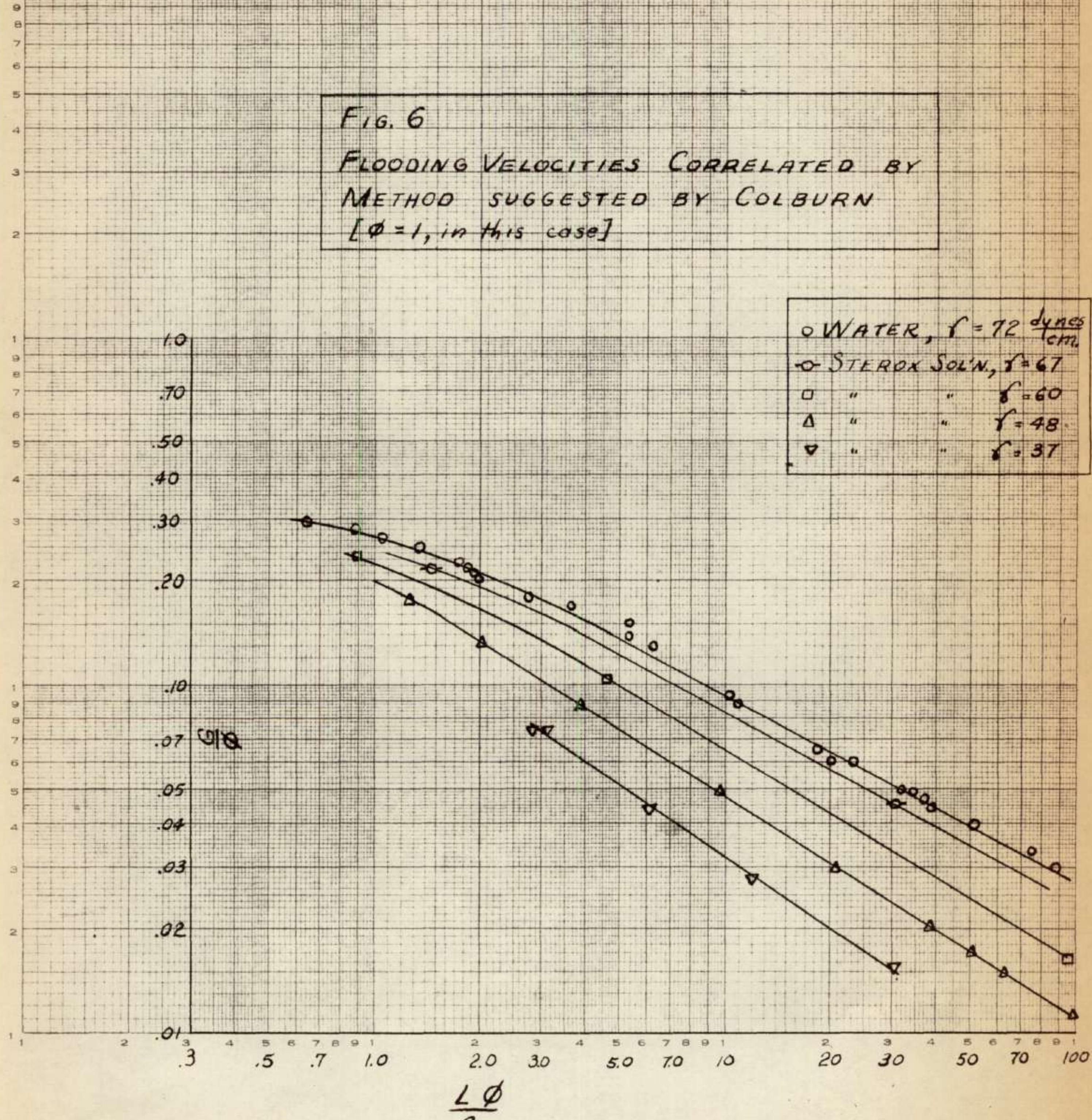
Fig. 6
Flooding Velocities Correlated by Method suggested by Colburn
[φ = 1, in this case]
○ Water, γ = 72 dynes/cm.
-○- Sterox Sol'n, γ = 67
□ " " γ = 60
Δ " " γ = 48
▽ " " γ = 37
1.0
.70
.50
.40
.30
.20
.10
.07
.05
.04
.03
.02
.01
.3
.5
.7
1.0
2.0
3.0
5.0
7.0
10
20
30
50
70
100
Lφ/G

since one packing was used and all the solutions, except toluene, had the same density and viscosity, it was useful. When plotted by the method of Sherwood, et al., the line falls about 30% above their line at low values of L/G and about 40% below at high values. This is very nearly the same result that was reached by Bain and Hougen[9] and Lobo, et al.[11] when they replotted all data available. By the method used by Schoenborn and Dougherty[10] the line falls below theirs by a constant factor of about .6, and this is certainly due in part to their use of visual flooding velocities, which, for $\frac{1}{2}$ inch packings, are always higher than graphical, as shown by Sarchet[8].

The great effect of lowering the surface tension can be seen in figures 5 and 6, where the lines are plotted for water and the solutions of sterox. It can also be seen that the effect appears to be proportional to the amount of lowering of the surface tension. The physical significance of this is thought to be that the lowering in surface tension is a measure of the tendency of the solution to foam or bubble. This conclusion was reached because of visual observation of the column in operation, for with the sterox solutions the foaming was more evident than with water, and was excessive in the case of the lowest surface tension solution. This would be the case with practically any wetting agent since sterox was developed as a minimum foaming detergent. This is covered more fully in "Discussion".

The runs with toluene show that with a liquid of low surface tension which does not tend to foam, the flooding rate is even higher than with water. This would be expected since the toluene wets the packing more thoroughly, and does not tend to channel as much as water, and the friction necessary to flood the column is therefore greater. The point to be emphasized is that the toluene has natural surface characteristics, while a sterox solution, even though the bulk of the liquid has the properties of water, has greatly altered surface characteristics, and when the flow is broken up in a column the surface characteristics become highly important.

The effect of lowering the surface tension is shown more directly in fig. 7 where G at flooding is plotted against surface tension of sterox solutions at constant values of L. It is also interesting to note in fig. 7 that, at high values of L the effect is greater in the low surface tension ranges, and at low values of L it is greater in the range near the surface tension of water.

As it was noted that the effect seemed to be proportional to the lowering in surface tension, and the lines were almost parallel to the lines for water, an empirical correlation was attempted. By trial and error, a power of the ratio of the surface tension of water to that of the solution was found, which brought all the points on to the water curve (within a range of deviations no greater than the water points themselves) when multiplied by the abscissa group, on the Sherwood, Shipley and Holloway type correlation. This factor to be included on the abscissa is thus $\left(\frac{\gamma_w}{\gamma_s}\right)^{2.6}$ shown in fig. 8.

On the Colburn type plot a factor was found to be included on the ordinate, $\left(\frac{\gamma_w}{\gamma_s}\right)^{1.8}$, but the deviations are more pronounced at the upper end of the curve, than in the Sherwood, et al. correlation. This is shown in fig. 9.

The data with toluene was not treated as it is limited and was

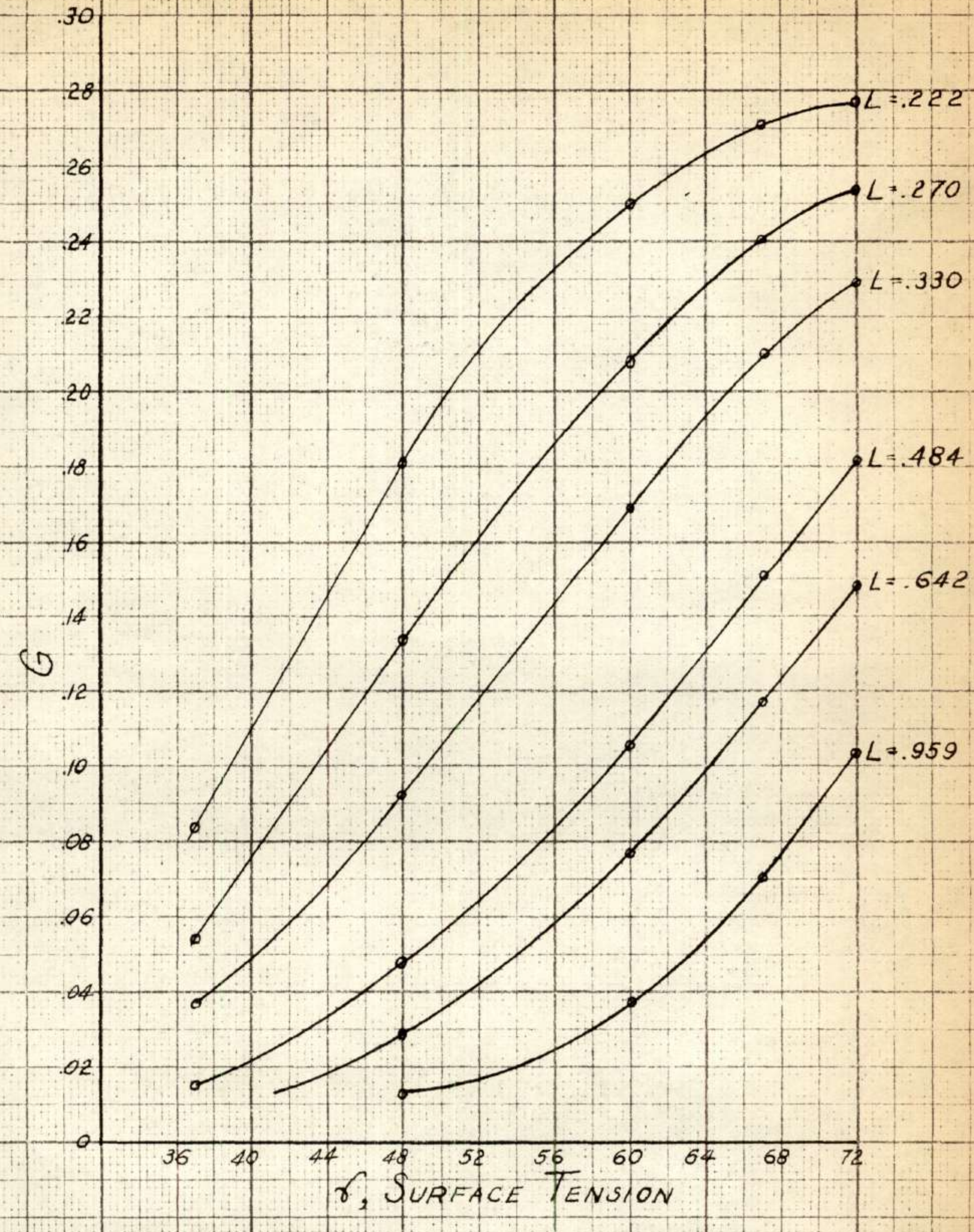

FIG. 7 PLOT OF GAS MASS VELOCITY AT FLOODING VS. SURFACE TENSION [AT CONSTANT LIQUID RATES]

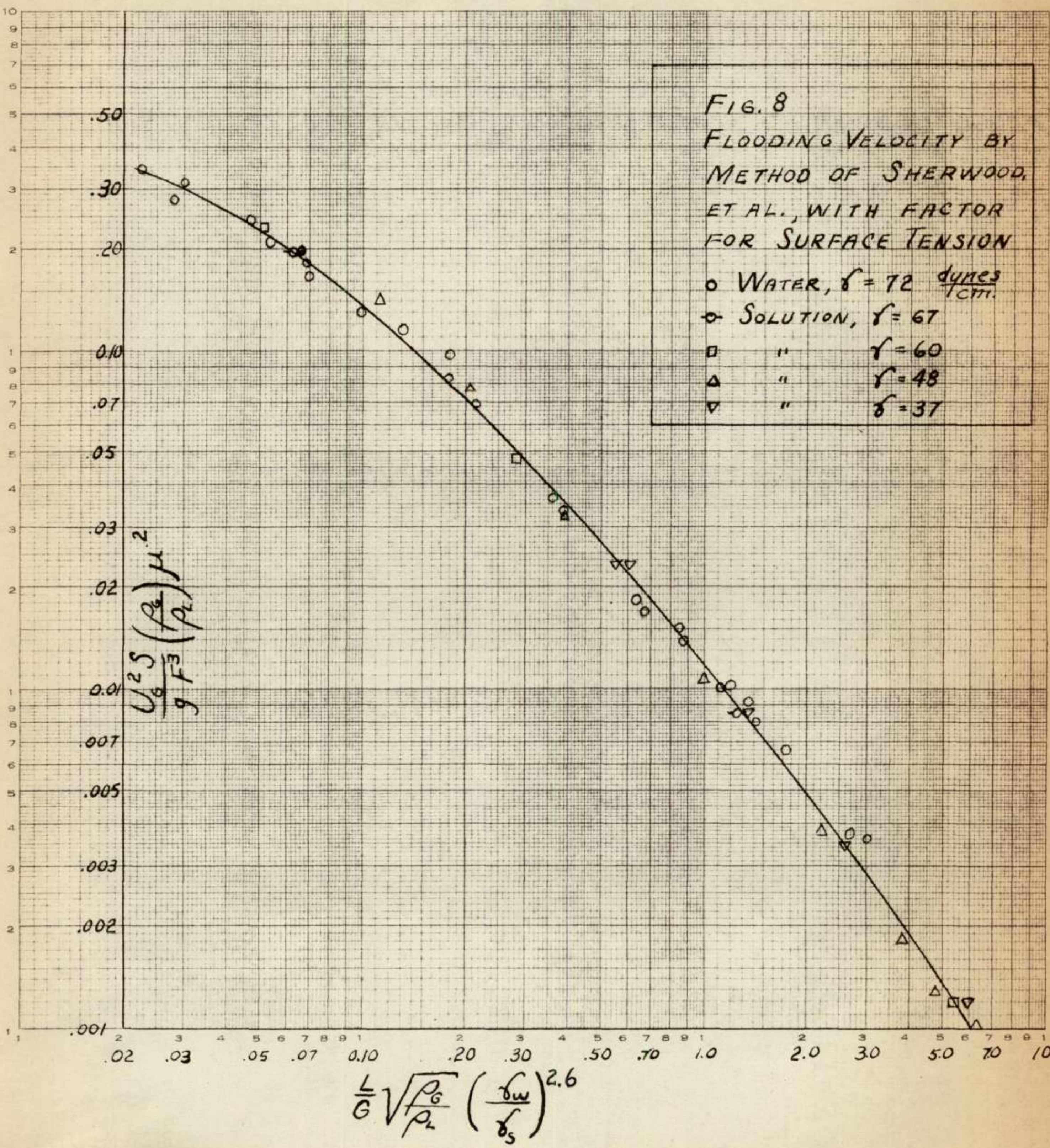
FIG. 8
FLOODING VELOCITY BY METHOD OF SHERWOOD, ET AL., WITH FACTOR FOR SURFACE TENSION
o WATER, γ = 72 dynes/cm.
SOLUTION, γ = 67
□ " γ = 60
△ " γ = 48
▽ " γ = 37
$\frac{U_G^2 S}{g F^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^2$
.50
.30
.20
0.10
.07
.05
.03
.02
0.01
.007
.005
.003
.002
.001
.02
.03
.05
.07
0.10
.20
.30
.50
.70
1.0
2.0
3.0
5.0
7.0
10
$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}\left(\frac{\gamma_w}{\gamma_s}\right)^{2.6}$

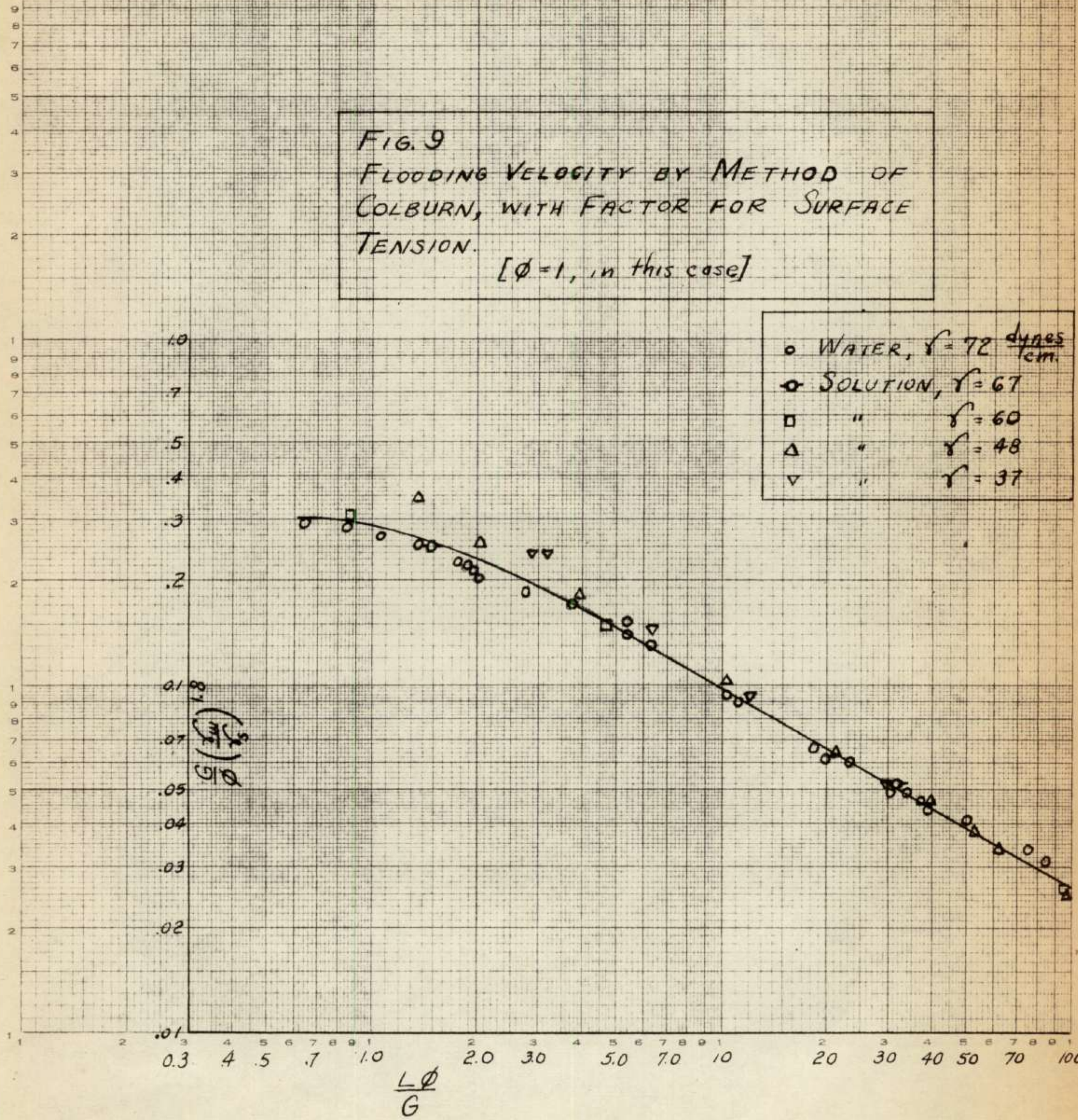
FIG. 9
FLOODING VELOCITY BY METHOD OF COLBURN, WITH FACTOR FOR SURFACE TENSION.
[Ø = 1, in this case]
o WATER, γ = 72 dynes/cm.
SOLUTION, γ = 67
□ " γ = 60
Δ " γ = 48
∇ " γ = 37
1.0
.7
.5
.4
.3
.2
0.1
.07
.05
.04
.03
.02
.01
0.3
.4
.5
.7
1.0
2.0
3.0
5.0
7.0
10
20
30
40
50
70
100
LØ/G

taken only to compare in a general way with the sterox solutions. It is indicative that the surface tension of any liquid has an effect on the flood point, but the effect is not as great as that of viscosity or density and thus may not affect preliminary design calculations except in extreme cases.

DISCUSSION

One point to be noted when using the correlation of Sherwood, Shipley, and Holloway is that the values of S and F (packing surface and void space, respectively) given in the literature vary widely, as noted by Lobo, et al.[11]. The main reason for this variance studied by Lobo and his colleagues was the method of packing the column. Some authors have used the manufacturer's figures for S and F, which are usually gotten by dry dumping in a cubic-foot box. If the column is packed while filled with liquid, the number of packing units per cubic foot of column may vary widely, and consequently S and F vary. It was thought necessary to very carefully measure S and F for this reason, and this was done.

The other discrepancy noted in some published work is due to the method of measuring S and F. A known amount of liquid may be poured over the dry packing and be held there, the height to which the liquid rises noted, and F calculated from this, since the volume of the column is known. If the surface area and volume of an individual packing unit is known, S may be found. The value of S/F^3 thus calculated is based on "dry voids". The other method is to measure the amount of liquid drained off the packing, after noting the height of liquid originally in the column. In this way some of the liquid will be retained on the packing in the form of droplets. This gives a measure of S and F based on "Drained wet voids".

These two methods did not give widely different results for this investigator, F based on dry voids being found to be 0.62, and based on drained wet voids to be 0.59 (the value based on dry voids was used in the correlation). Some investigators, however, have found F by the two methods described above to vary as much as from 0.54 (wet voids) to .75 (dry voids). This does not seem logical to this writer, as the amount of water retained by the packing in the drained wet method certainly does not appear to be of this magnitude.

The work of Lobo and his colleagues[11] eliminates all the error of this sort, if the dry voids are carefully measured. Some authors have used drained wet voids on the premise that it more nearly approximates the actual condition of the column in operation. This may be true but it moves the curve by a constant factor, so either method could be used as long as it is specified. Since the final correlation of Lobo et al., is based on dry voids, and their method shows less average deviation than the others, it was decided that dry voids was the best measure of F.

The next point to be discussed is the correlation found in this thesis for low surface tension solutions. It must be remembered that other surface active agents may cause a different amount of foaming in the column, and the correlation is for sterox solutions alone. This type of correlation, however, would certainly be a starting point for future work on other surface active agents.

It should be stated also, that sterox is a minimum foaming detergent, and others may have an even greater effect. As other detergents are developed, the foaming problem may be eliminated entirely; however, the tendency to foam is a natural corollary to reducing the surface tension, if the following explanation of foaming is accepted.

The basic explanation of foaming is thought to be this: as the molecules of a surface active material, most of which are dipolar, congregate at the surface of the solvent, and reduce the surface energy, they orient themselves so that one of the poles of the dipolar molecule tends to protrude from the surface. This puts a charge on the surface, which is not present with the random orientation of pure liquid molecules. When flow is interrupted and bubbles tend to form, the bubbles of a pure liquid coalesce, whereas those of solution of a surface active agent repel each other, and the foam is thus stable. This phenomenon occurs with soaps and most detergents.

This investigation is concerned primarily with flooding velocity. Pressure drop in the column is treated only as far as is necessary to determine flooding, however, it should be reported here that the pressure drop at flooding is consistently less with the sterox solutions than with water of toluene. This in no way affects the results, but may be of interest to other workers, or in design calculations.

It is felt that the results of this investigation should be of interest to design engineers. Solutions containing surface active agents, even in very small amounts, could be used in packed columns with embarrassing results. If a column were designed for pure liquids, it would certainly flood prematurely, with any detergent in the liquid.

CONCLUSIONS

From the results of this investigation the following conclusions were drawn:

1. The surface tension of the liquid has an appreciable effect on flooding velocities in columns packed with $\frac{1}{2}$ inch Berl saddles.

2. This effect is greater when the surface tension of a liquid is altered by the addition of a surface active agent than when a liquid of naturally low surface tension is used. The effect on the flooding velocity of lowering the surface tension with a surface active agent may be as great as 300%.

3. A correlation for the effect of surface tension may be found for the surface active agent used (sterox SK) by multiplying one coordinate of a general correlation by a power function of the ratio of the surface tension of water to the surface tension of the solution.

4. Column diameter probably has an effect on flooding velocity, since the investigators who used small (2 inch) columns showed different results from those who used larger columns.

5. The nature of the surface active agent probably affects the flooding velocity also, since some tend to foam more than others.

RECOMMENDATIONS

It is recommended that further systematic study of the effect of surface tension on flooding velocities be undertaken due to the magnitude of the effect found in this investigation. It is further recommended that the effect of column diameter be studied, due to the discrepancies in published work which appear to be due to this factor.

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APPENDIX

DATA

T_a = Air Temperature T_w = Liquid Temperature

L (#/sec.ft^2)	G (#/sec.ft^2) Graphical	G (#/sec.ft^2) Visual	T_a °F	T_w °F
WATER, γ = 72				
0.185	0.290	0.290	57	66
0.241	0.284	0.284	64	65
0.270	0.256	0.256	55	61
0.340	0.250	0.250	55	61
0.396	0.210	0.230	65	65
0.396	0.225	0.225	57	57
0.396	0.200	0.230	55	55
0.407	0.222	0.232	70	65
0.484	0.177	0.206	63	65
0.642	0.170	0.190	53	52
0.726	0.140	0.186	72	65
0.803	0.155	0.175	65	65
0.803	0.130	0.165	70	65
0.959	0.094	0.094	65	65
0.959	0.088	0.088	54	60
1.189	0.065	0.075	67	55
1.189	0.060	0.075	55	61
1.419	0.060	0.060	65	60
1.419	0.060	0.088	70	65
1.565	0.050	0.066	70	65
1.717	0.044	0.074	65	65
1.717	0.050	0.072	60	66
1.861	0.048	0.065	61	66
2.010	0.040	0.070	60	63
2.010	0.040	0.060	68	60
2.310	0.034	0.064	70	65
2.650	0.030	0.036	65	65
2.660	0.300	0.036	65	65
STEROX SOLUTION γ = 48				
0.225	0.185	0.340	64	65
0.270	0.136	0.162	63	67
0.340	0.088	0.122	63	67
0.484	0.050	0.063	63	65
0.642	0.030	0.043	65	65
0.803	0.021	0.032	65	65
0.959	0.019	0.024	61	65
0.959	0.016	0.017	61	66
1.120	0.012	0.016	61	65

L ($\#/sec.ft^2$)	G ($\#/sec.ft^2$) Graphical	Visual	T_a ^oF	T_w ^oF
STEROX SOLUTION	γ = 37			
0.209	0.075	0.100	70	68
0.242	0.075	0.115	70	68
0.270	0.044	0.072	70	68
0.328	0.028	0.038	67	66
0.490	0.016	0.016	67	66
STEROX SOLUTION	γ = 67			
0.330	0.225	0.235	65	64
1.420	0.046	0.071	65	64
STEROX SOLUTION	γ = 60			
1.585	0.017	0.020	70	68
0.484	0.105	0.126	70	68
0.220	0.250	0.250	70	68
TOLUENE γ = 29				
2.229	0.080	0.084	56	55
1.300	0.110	0.121	57	55
0.333	0.205	0.205	57	55
0.211	0.230	0.235	57	55

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0.396	0.200	0.230	55	55
0.407	0.222	0.232	70	65
0.484	0.177	0.206	63	65
0.642	0.170	0.190	53	52
0.726	0.140	0.186	72	65
0.803	0.155	0.175	65	65
0.803	0.130	0.165	70	65
0.959	0.094	0.094	65	65
0.959	0.088	0.088	54	60
1.189	0.065	0.075	67	55
1.189	0.060	0.075	55	61
1.419	0.060	0.060	65	60
1.419	0.060	0.088	70	65
1.565	0.050	0.066	70	65
1.717	0.044	0.074	65	65
1.717	0.050	0.072	60	66
1.861	0.048	0.065	61	66
2.010	0.040	0.070	60	63
2.010	0.040	0.060	68	60
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